Liquefaction Triggering Evaluations at DOE Sites – An Update

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Agenda

- Background
- Purpose and Objectives
- Liquefaction Triggering Methods
- Site Evaluations for SRS
- Conclusions

Background

Background

- This presentation is an update of a presentation given at the 2011 DOE Natural Phenomena Hazards meeting and discusses advancements in the field of liquefaction evaluations as relates to DOE sites.
- These new advances include:
  - New additions by Boulanger and Idriss (2014) including MSF and fines content correction for CPT
  - New additions by Kayen et al. (2013), with respect to V_s
  - Application of aging factors

Background – Definition of Terms

- This presentation focuses on the liquefaction potential of seismically induced cyclic loading on cohesionless materials. The liquefaction, or cyclic softening, potential of cohesive materials is not addressed in this presentation.

- The publications by Youd and Idriss (1997), Andrus and Stokoe (2000), Youd et al. (2001), and Youd et al. (2003) are jointly referred to herein as “NCEER”.

Background

- Liquefaction triggering methods use either standard penetration test (SPT), cone penetration test (CPT), or shear wave velocity (V_s) to estimate resistance to liquefaction. The triggering methods are summarized by input type below.
  - SPT
    - Youd et al. 2001 (NCEER)
    - Cetin et al. 2004 (Cetin)
    - Idriss and Boulanger 2008 (IB2008)
    - Boulanger and Idriss 2014 (BI2014)
  - CPT
    - Youd et al. 2001 (NCEER)
    - Moss et al. 2006 (Moss)
    - Idriss and Boulanger 2008 (IB2008)
    - Boulanger and Idriss 2014 (BI2014)
    - SRS Site-Specific
  - V_s
    - Youd et al. 2001 (NCEER)
    - Andrus et al. (2009)
    - Kayen et al. 2013 (Kayen)
- This update will focus on methods used at SRS, and the changes that have taken place since the previous presentation in 2011.

Purpose and Objectives

Purpose & Objectives

- The purpose of this presentation is to compare the liquefaction triggering methods utilizing the three types of input data (SPT, CPT, and V_s) using actual subsurface data obtained from project work at the Savannah River Site (SRS) in South Carolina.
- Additionally, liquefaction results accounting for soil aging will be addressed utilizing the method developed specifically for SRS (WSRC 2008) compared to the methodology developed by Andrus and his colleagues using shear wave velocity data, and recent work reported by Green and his colleagues from Christchurch.
- The objective is to assess the magnitude of the differences in each of the methods and types of input data to determine the impact of those differences, given the inherent uncertainty in liquefaction potential assessments.

Liquefaction Triggering Methods (a brief background)

Liquefaction Triggering Methods

- For the liquefaction triggering methods presented herein, the factor of safety against liquefaction is defined as:
  - $FS = \frac{CRR_{7.5}}{CSR} * MSF * K_{\sigma} * K_{\alpha} * K_{age}$
  - Where:
    - » CSR is the earthquake demand
    - » CRR is the soil's capacity (resistance or strength)
    - » MSF is the magnitude scaling factor
    - » K_{σ} is a correction for overburden pressure
    - » K_{α} is a correction for static shear stress (set to 1 for this comparison)
    - » K_{age} is a correction for age (also known as K_{DR} set to 1 for the comparison unless otherwise noted)
- Liquefaction triggering methods generally present a simplified method to approximate the CSR. Liquefaction triggering methods generally recommend the use of site response where proper data are available. For this presentation, the results of site response analyses were performed and are used as input CSR.

Liquefaction Triggering Methods

- Recent changes/new developments
  - New fines content correction for BI2014 for CPTs.
  - New magnitude scaling factor (MSF) based on dilational response or relative density have been published by Cetin and Bilge (2012), Kishida and Tsai (2014), and BI2014. See these papers for details. This presentation will briefly discuss the MSF published by BI2014 for CPTs and SPTs.
  - New/updated age corrections.

Fines Content Correction – CPT Cont.

- $q_{c1Ncs} = q_{c1N} + \Delta q_{c1N}$
  - BI2014
- $\Delta q_{c1N} = \left(11.9 + \frac{q_{c1N}}{14.6}\right) e^{\left(1.63 - \frac{9.7}{FC+2} - \left(\frac{15.7}{FC+2}\right)^2\right)}$
  - BI2014

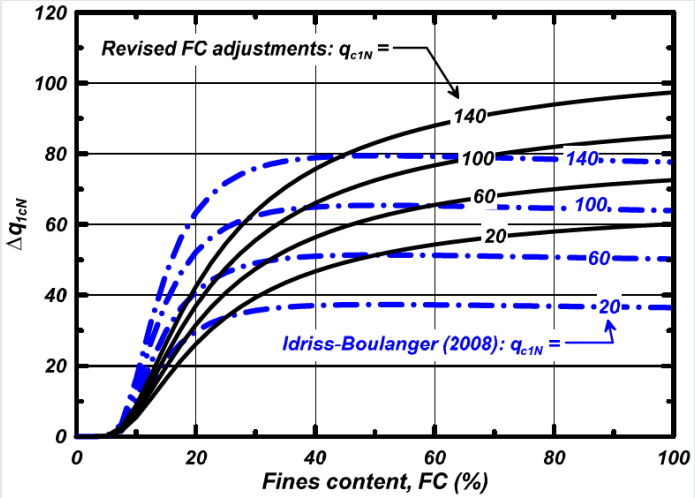
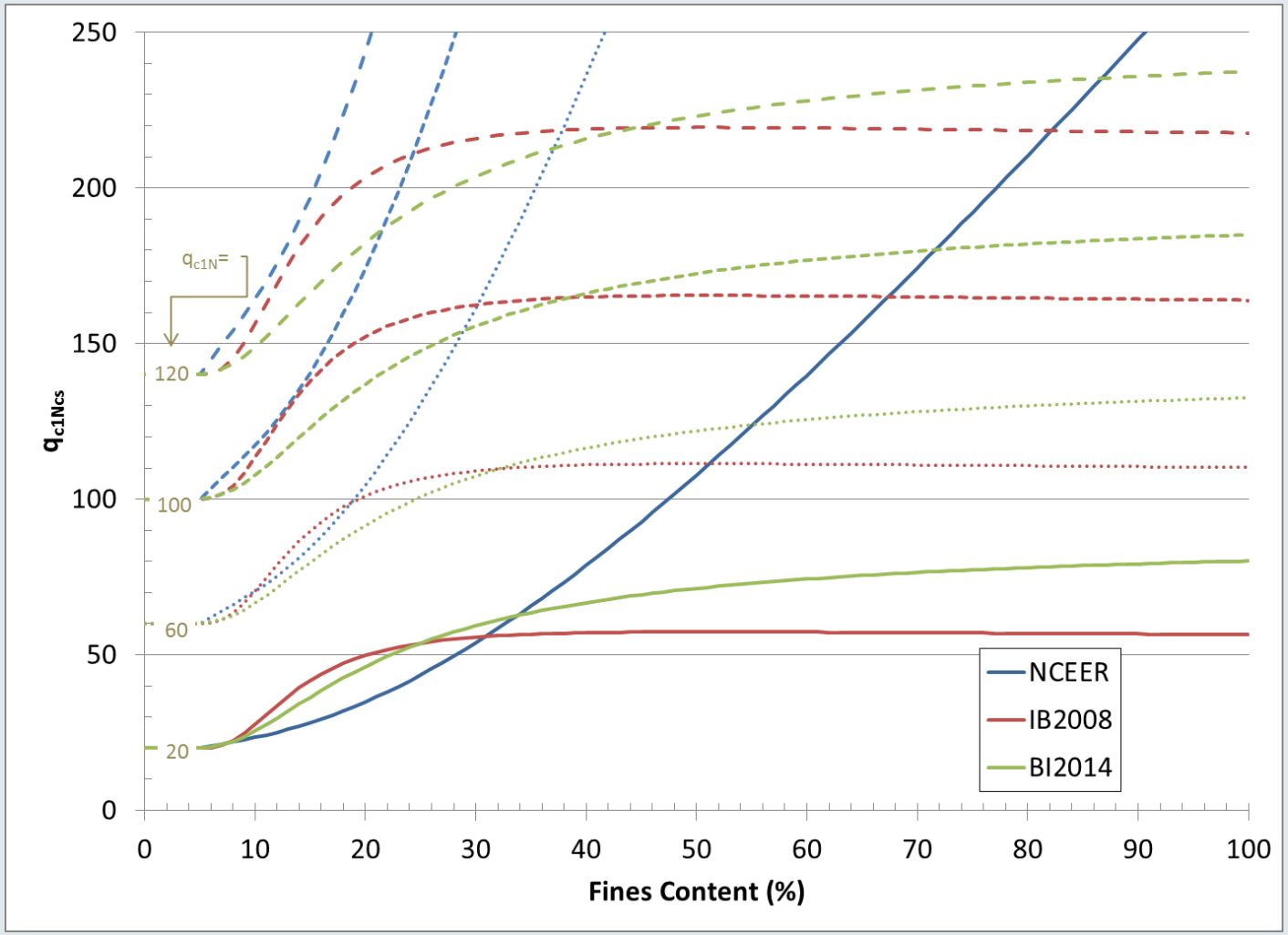


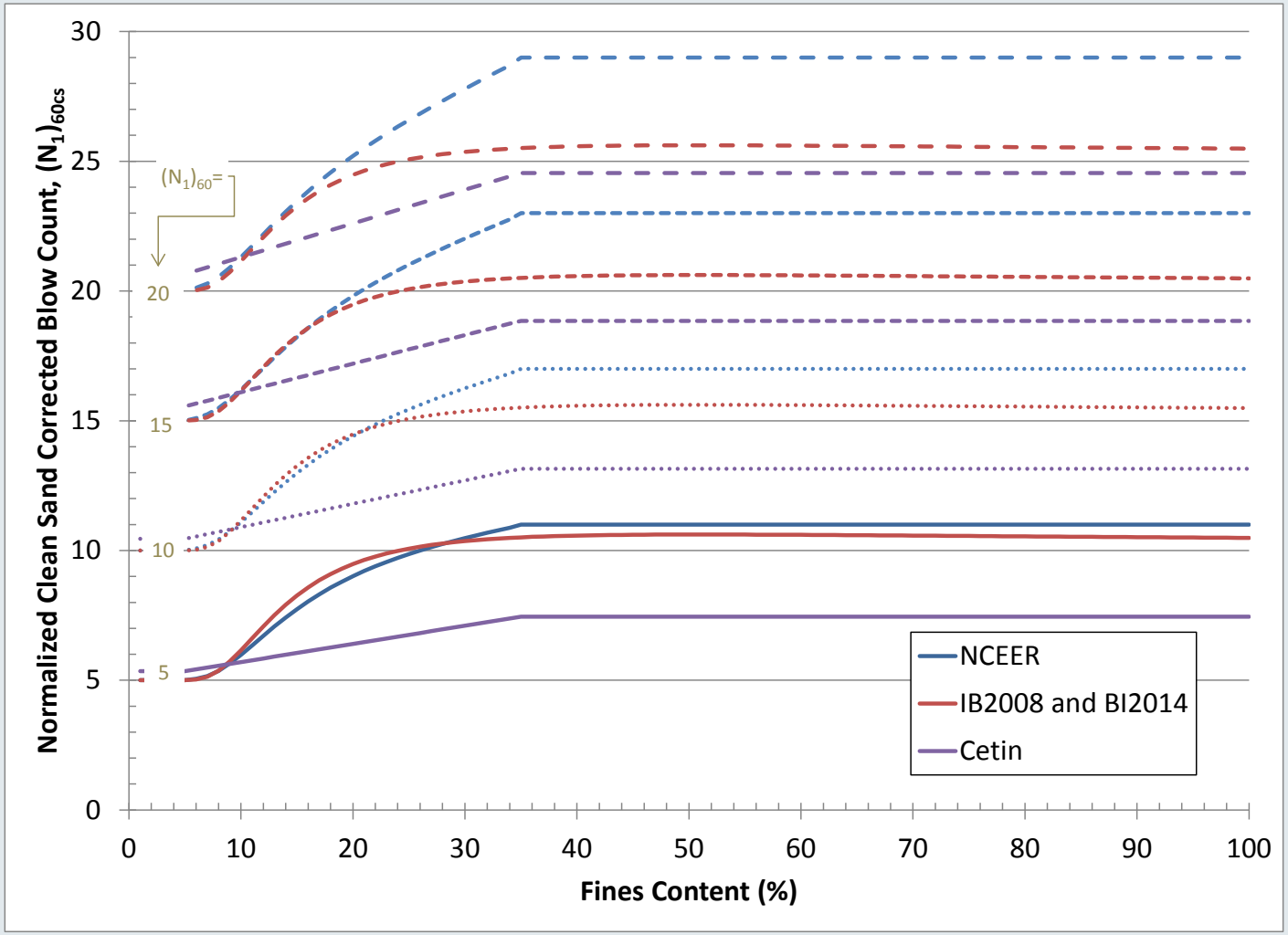
Figure 2.7a from BI2014

Fines Content Correction – CPT Cont.



Assumes I_c-apparent fines content correlation from Robertson and Wride (1998) for NCEER
Moss does not allow for this type of comparison due to the dependence on CSR.

Fines Content Correction – SPT



Magnitude Scaling Factor

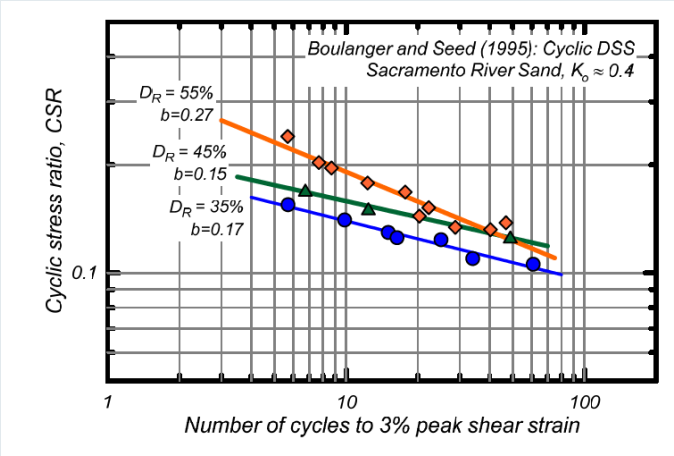
- IB2014 – “Magnitude scaling factor (MSF) relationships are used in liquefaction triggering correlations to approximately account for how the characteristics of the irregular cyclic loading produced by different magnitude earthquakes affect the potential for triggering of liquefaction.”

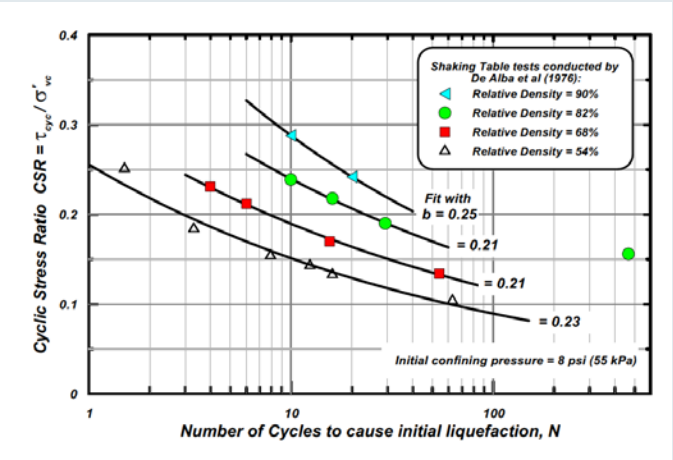
- This can be shown as:

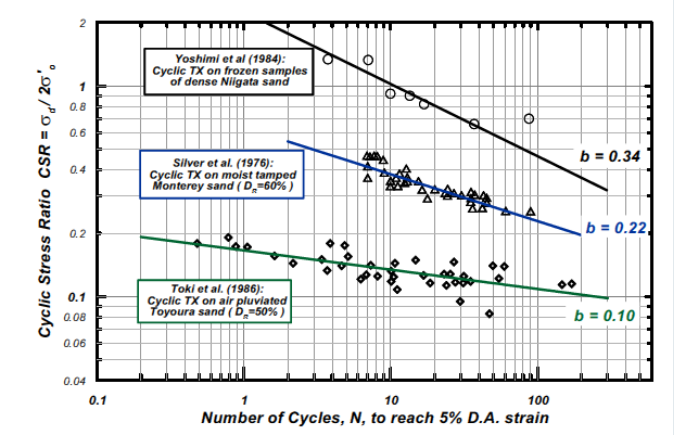
$$MSF = \frac{CRR_M}{CRR_{M=7.5}} = \left(\frac{N_{M=7.5}}{N_M}\right)^b$$

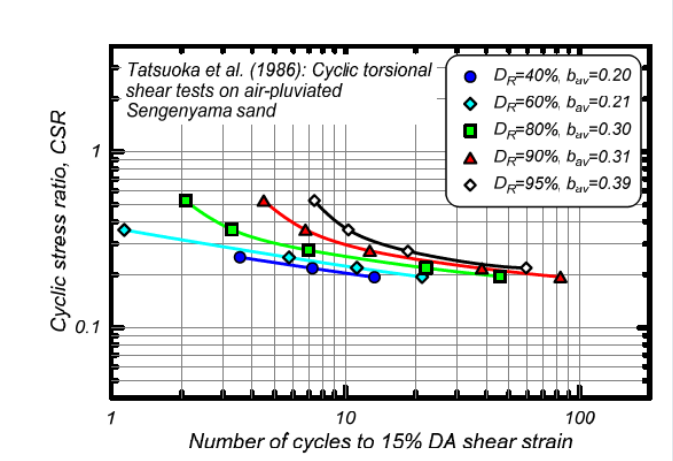
  - CRR_M = CRR at a given magnitude
  - CRR_M =7.5 = CRR at M=7.5
  - $N_{M=7.5}$ = number of uniform cycles for M = 7.5
  - N_M = number of uniform cycles for a given magnitude
  - b = fitting parameter

Magnitude Scaling Factor



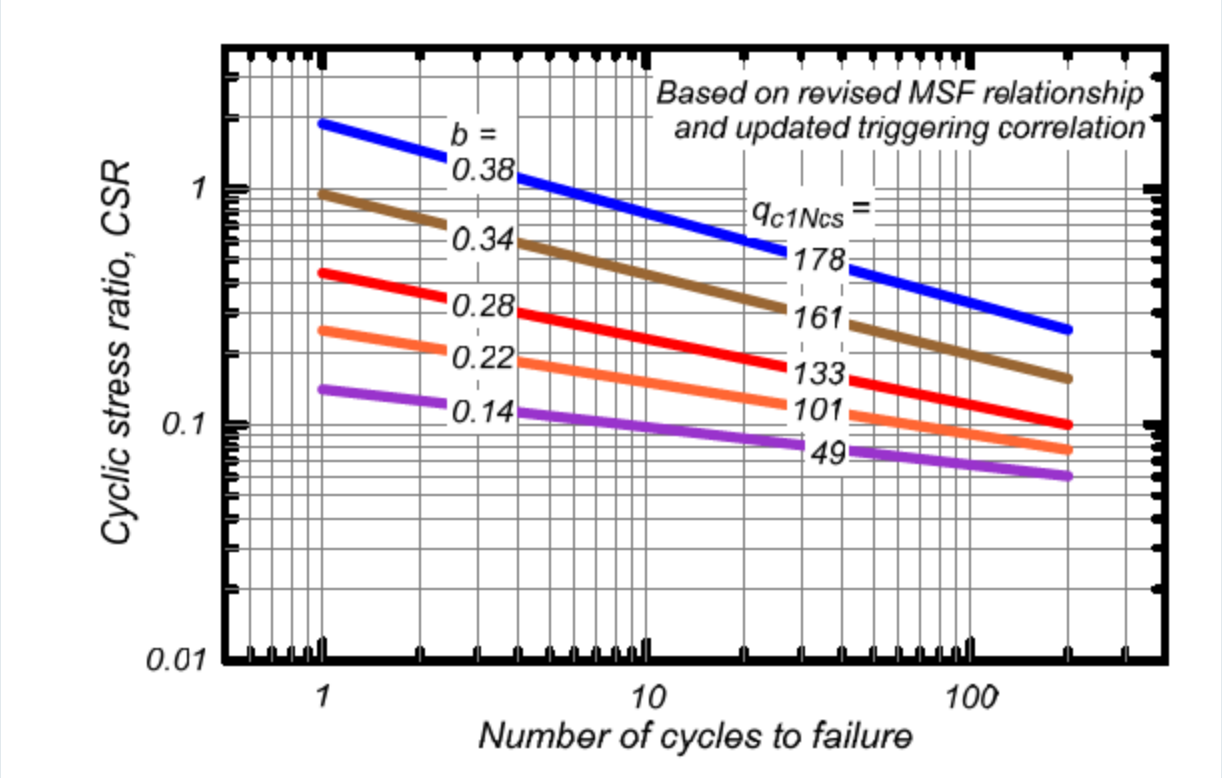






As reported by BI2014

Magnitude Scaling Factor



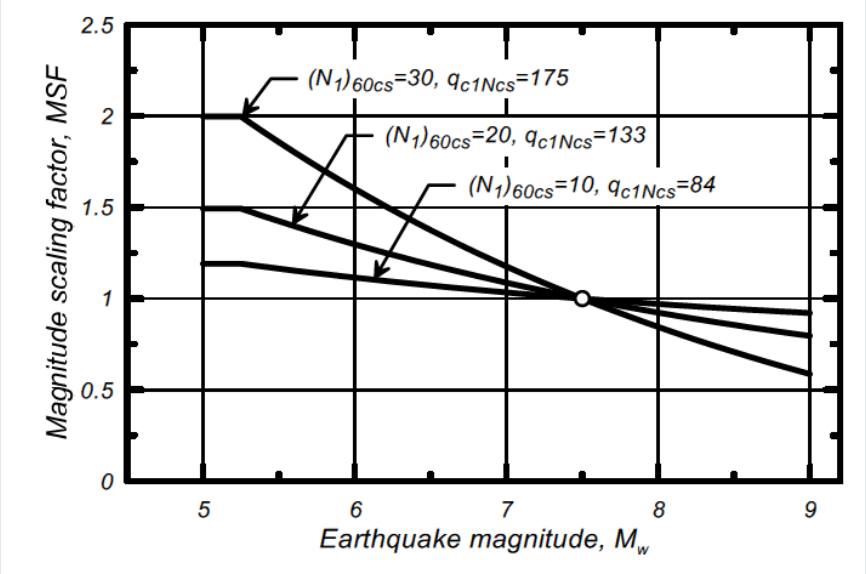
Interpretation as reported by BI2014

Magnitude Scaling Factor

- BI2014
- $MSF = 1 + (MSF_{max} - 1)\left(8.64e^{\left(\frac{-M}{4}\right)} - 1.325\right)$

- Where:
  - $MSF_{max} = 1.09 + \left(\frac{q_{c1Ncs}}{180}\right)^3 \leq 2.2$

- Or:
  - $MSF_{max} = 1.09 + \left(\frac{(N_1)_{60cs}}{31.5}\right)^2 \leq 2.2$

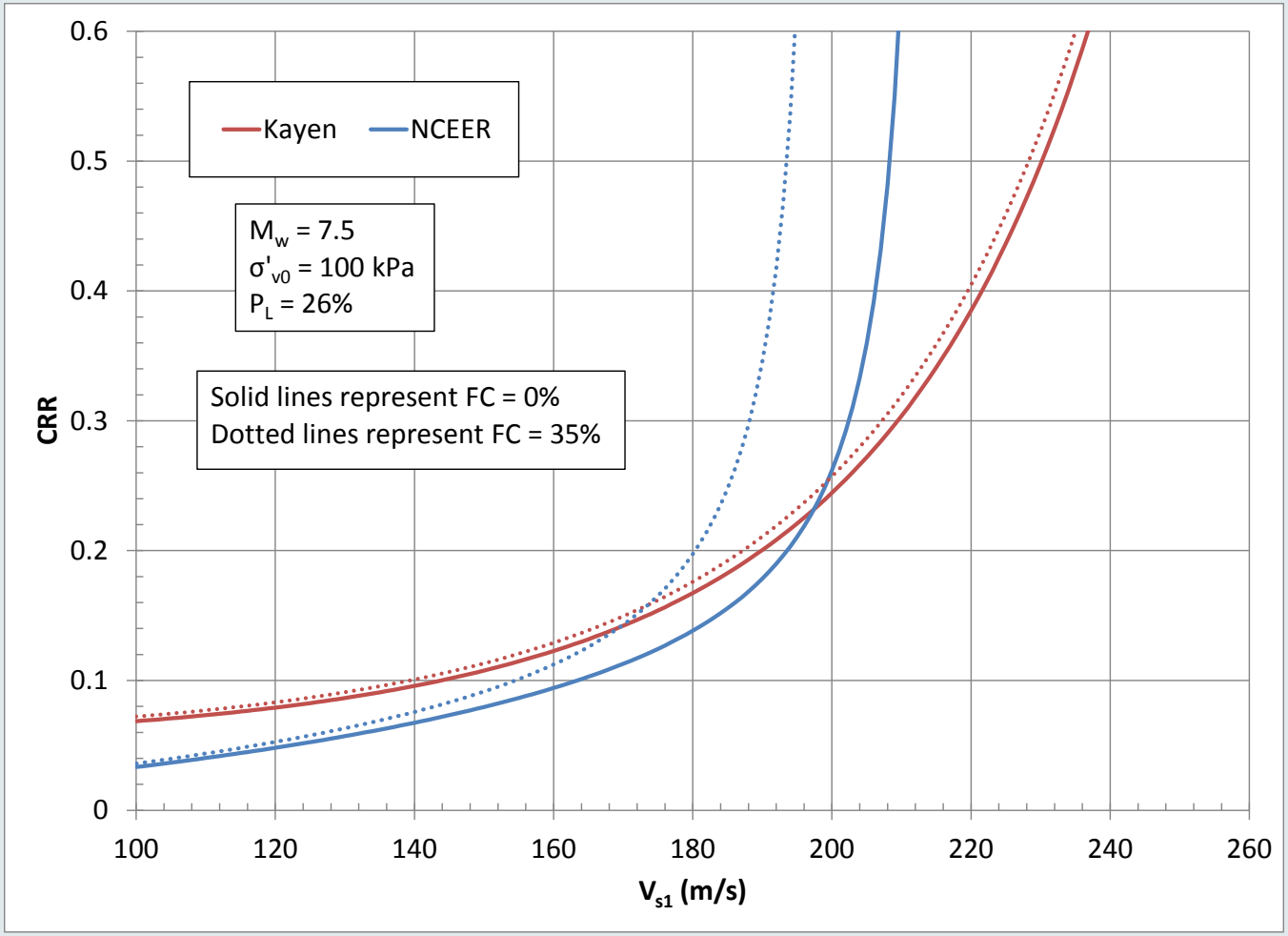


From BI2014

Liquefaction Triggering Methods

- Shear Wave Velocity

Shear Wave Velocity



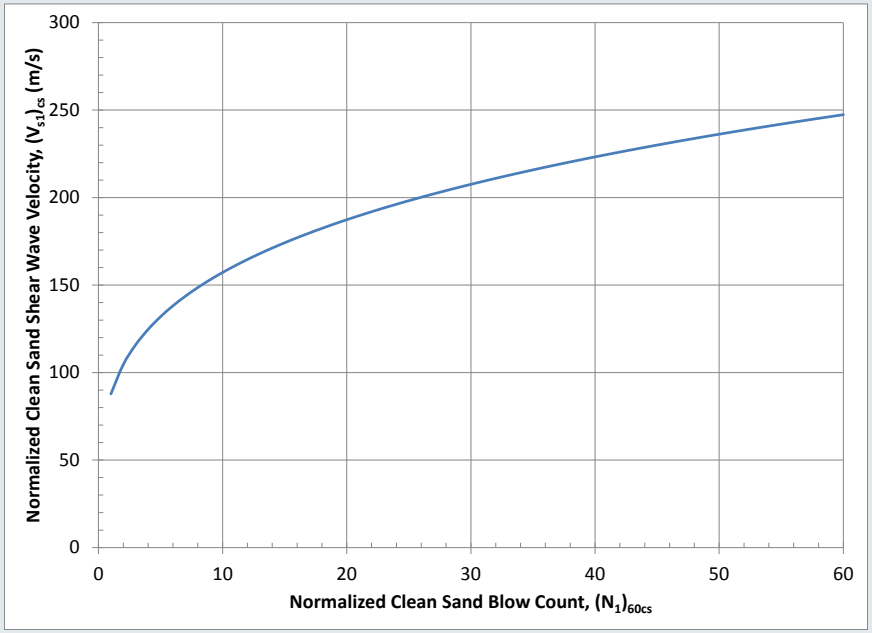
Relations shown are for Holocene sands

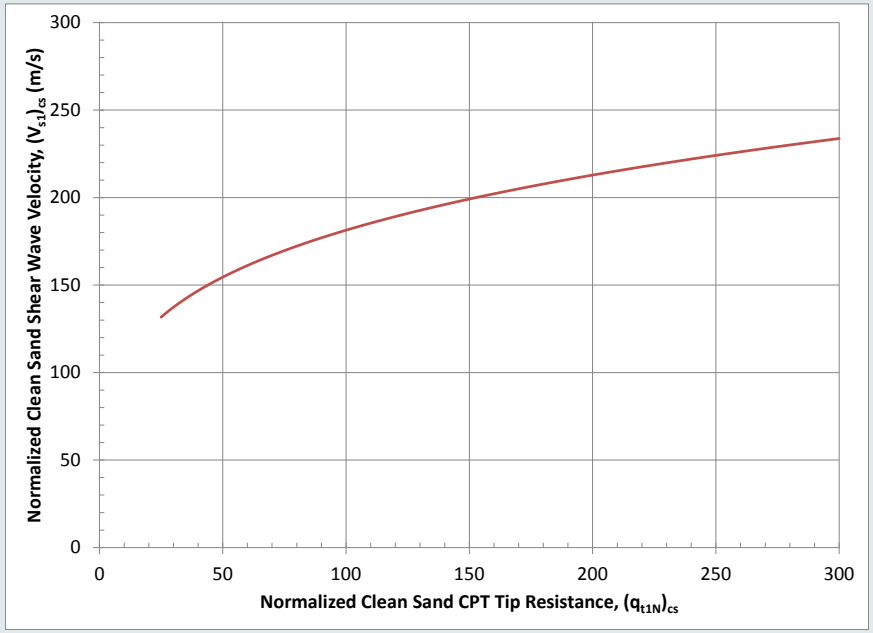
Aging

- Cyclic resistance has been shown to increase with time since initial deposition or last critical disturbance (also referred to as age).
- $CRR_k = CRR * K_{DR}$
  - CRR_k = Cyclic resistance ratio corrected for age and cementation
  - CRR = Cyclic resistance ratio uncorrected for age and cementation
  - K_{DR} = Factor to correct for influence of age and cementation on deposit resistance, also referred to as K_{age}

Aging – Andrus et al. (2009)

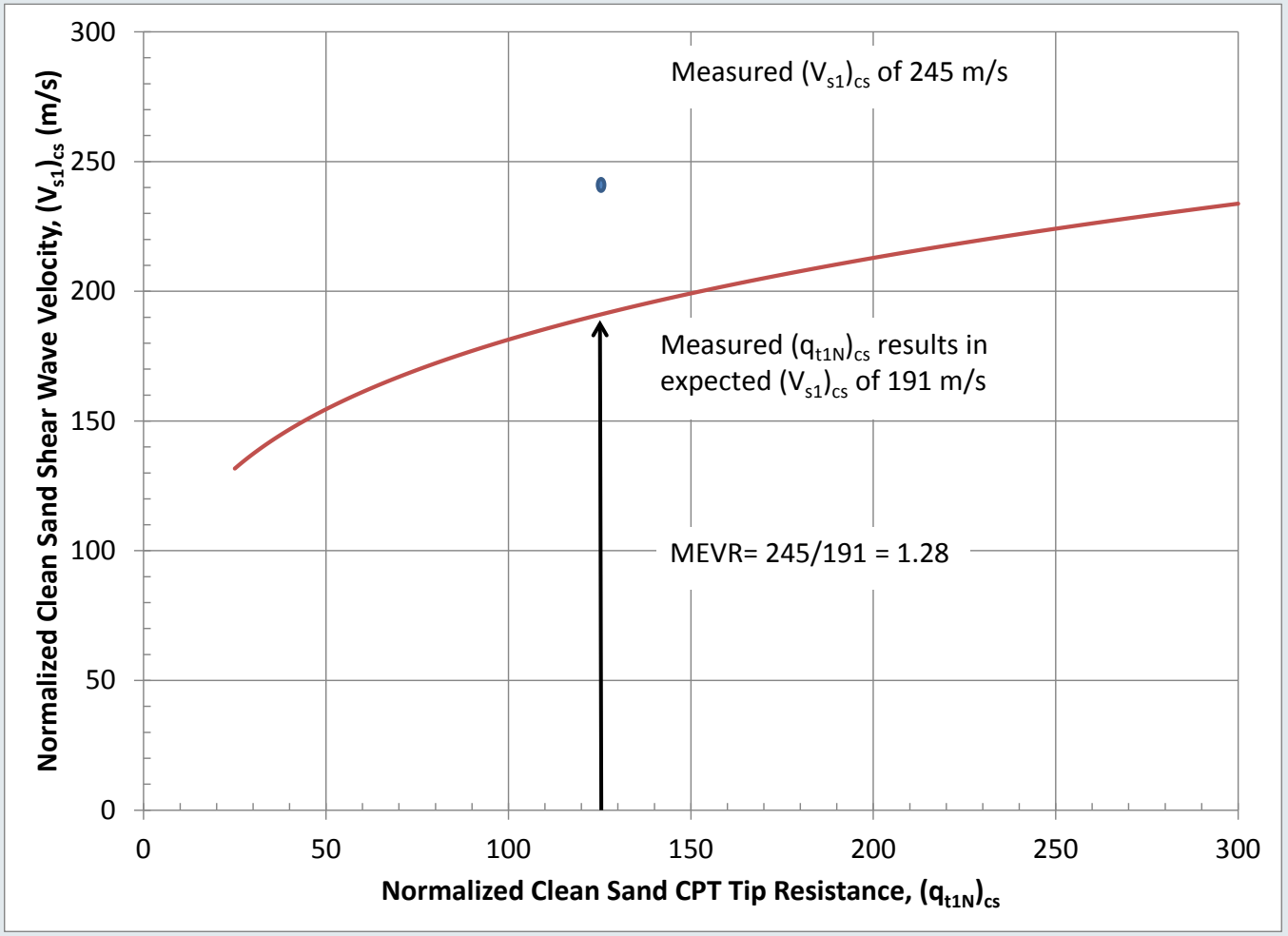
- Andrus et al. (2009) suggest a method using the ratio of measured to estimated shear-wave velocity (MEVR) to calculate a correction factor for liquefaction resistance.
- $$MEVR = \frac{Measured\ Shear\ Wave\ Velocity}{Estimated\ Shear{-}Wave\ Velocity\ based\ on\ Penetration\ Resistance}$$





Aging – Andrus et al. (2009)

- Example using inputs of $(q_{t1N})_{cs}$ = 125 and $(V_{1s})_{cs}$ = 245 m/s

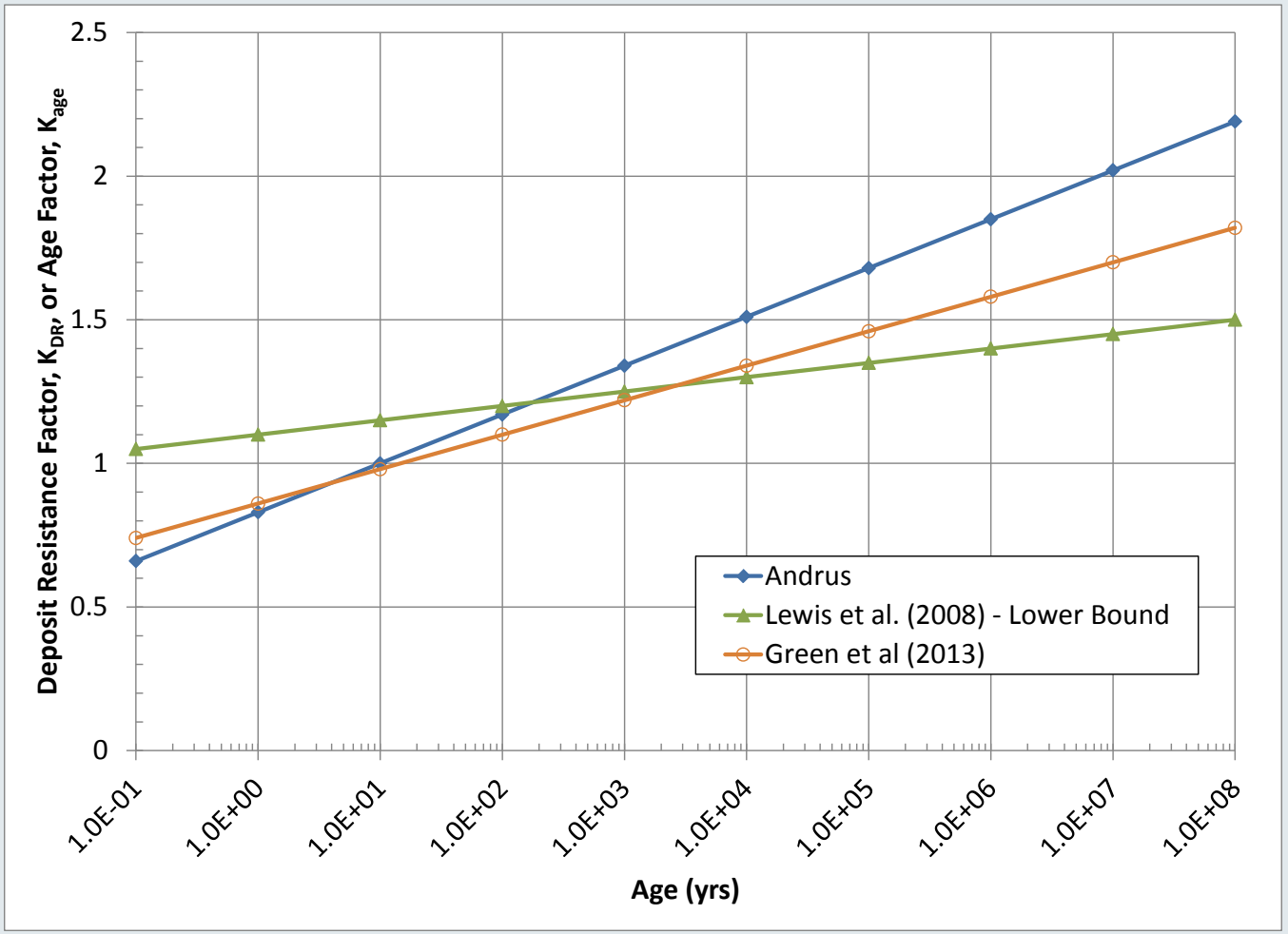


Aging – Andrus et al. (2009)

- Aging factor calculated using Andrus et al. (2009)
  - $K_{DR} = 2.07(MEVR) - 1.11$

- The cyclic resistance ratio is then calculated using the equation below after Andrus et al. (2009)
  - $CRR = 0.022\left(\frac{V_{S1}}{100(MEVR)}\right)^2 + 2.8\left(\frac{1}{V_{S1}^* - \frac{V_{S1}}{MEVR}} - \frac{1}{V_{S1}^*}\right)K_{DR}$
    - » V_{s1} = normalized shear wave velocity
    - » V_{s1}^* =
      - » 215 m/s for FC ≤ 5%
      - » 215-0.5(FC-5) m/s for 5% < FC ≤ 35%
      - » 200 m/s for FC > 35%

Aging



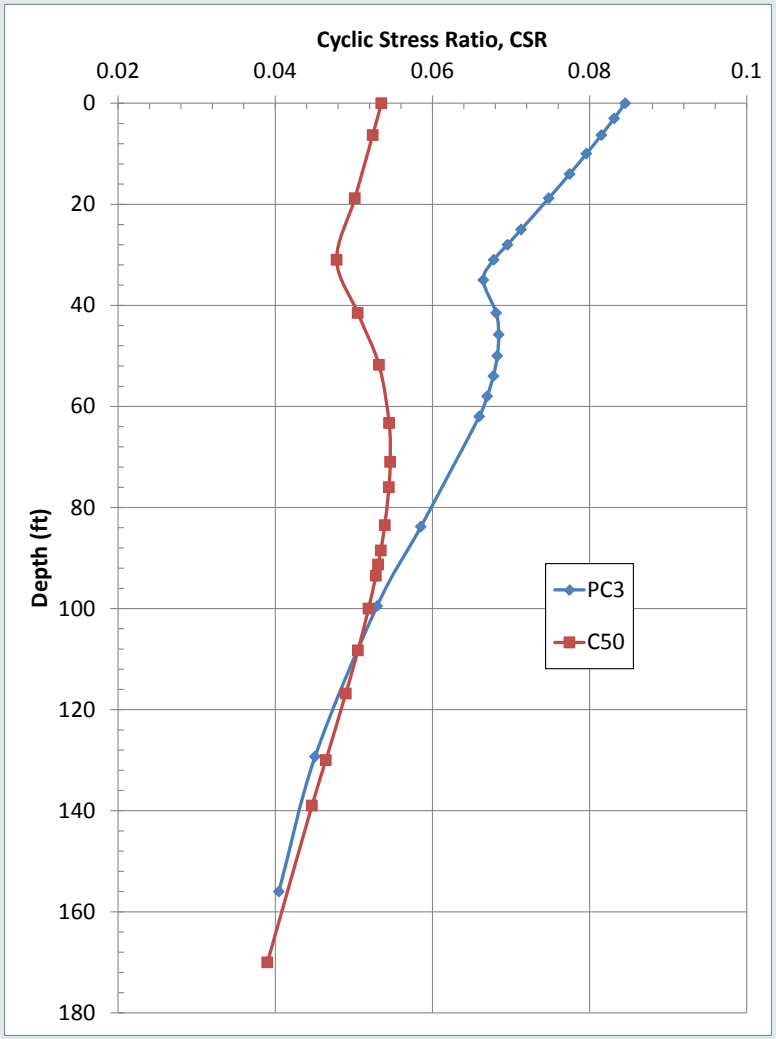
Green et al. (2013) notes: "It can be seen…that while the aging-relations have relatively similar slopes, their reference ages (i.e., K_{DR}=1) range from 2 days to 23 years, reflecting different manners of development and different indented uses."

Evaluations at SRS

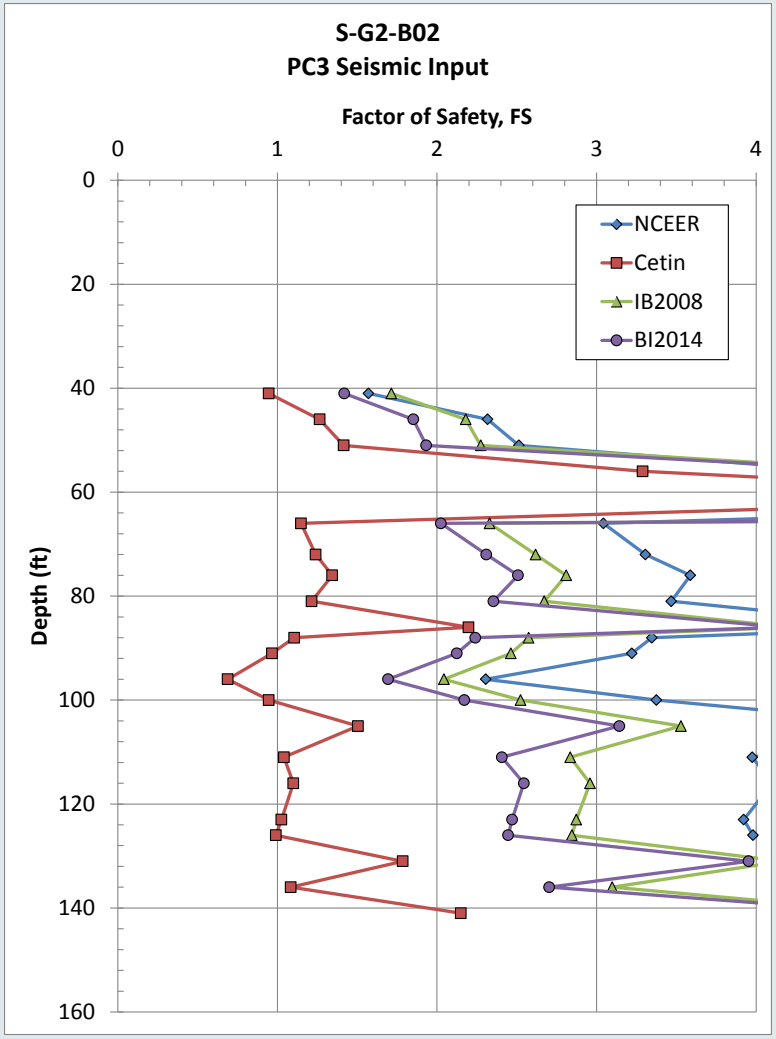
Site Evaluations at SRS

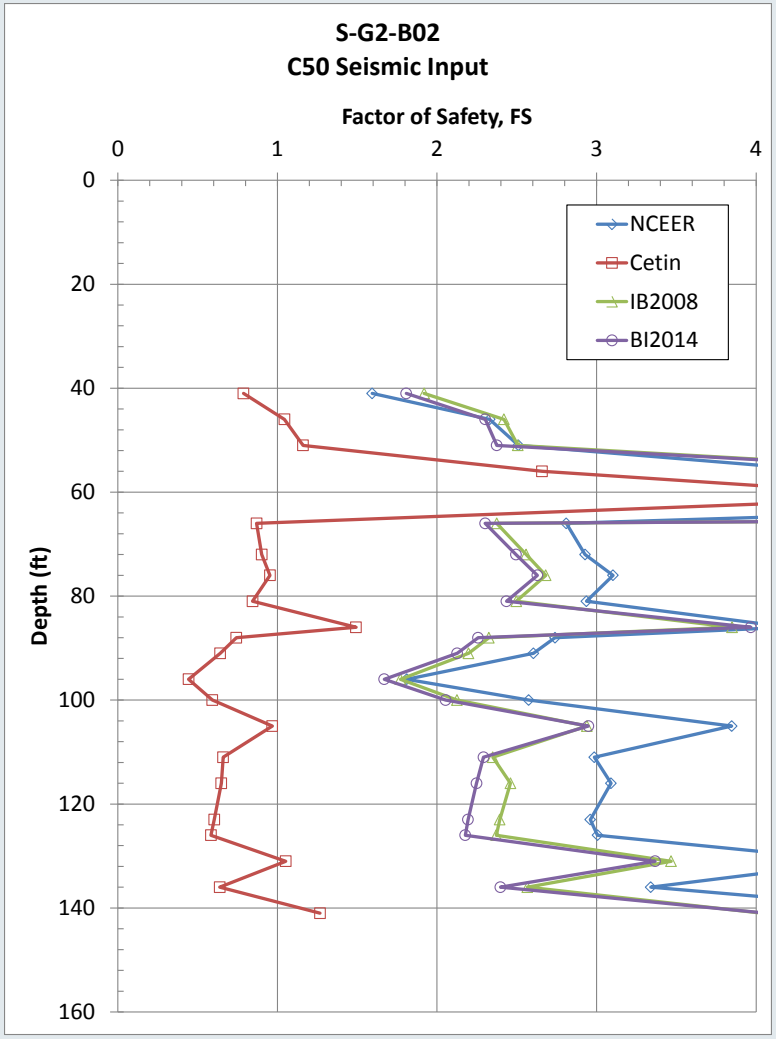
- The seismic demand or cyclic stress ratio (CSR) through the soil column is calculated using a one dimensional site response analysis.
- Two earthquakes are utilized
  - Deterministic
    - M_w = 7.2; PGA = 0.1g Charleston 50th (C50)
  - Probabilistic
    - M_w = 6.6, PGA = 0.2g Design Basis Event (PC3)

Site Evaluations at SRS



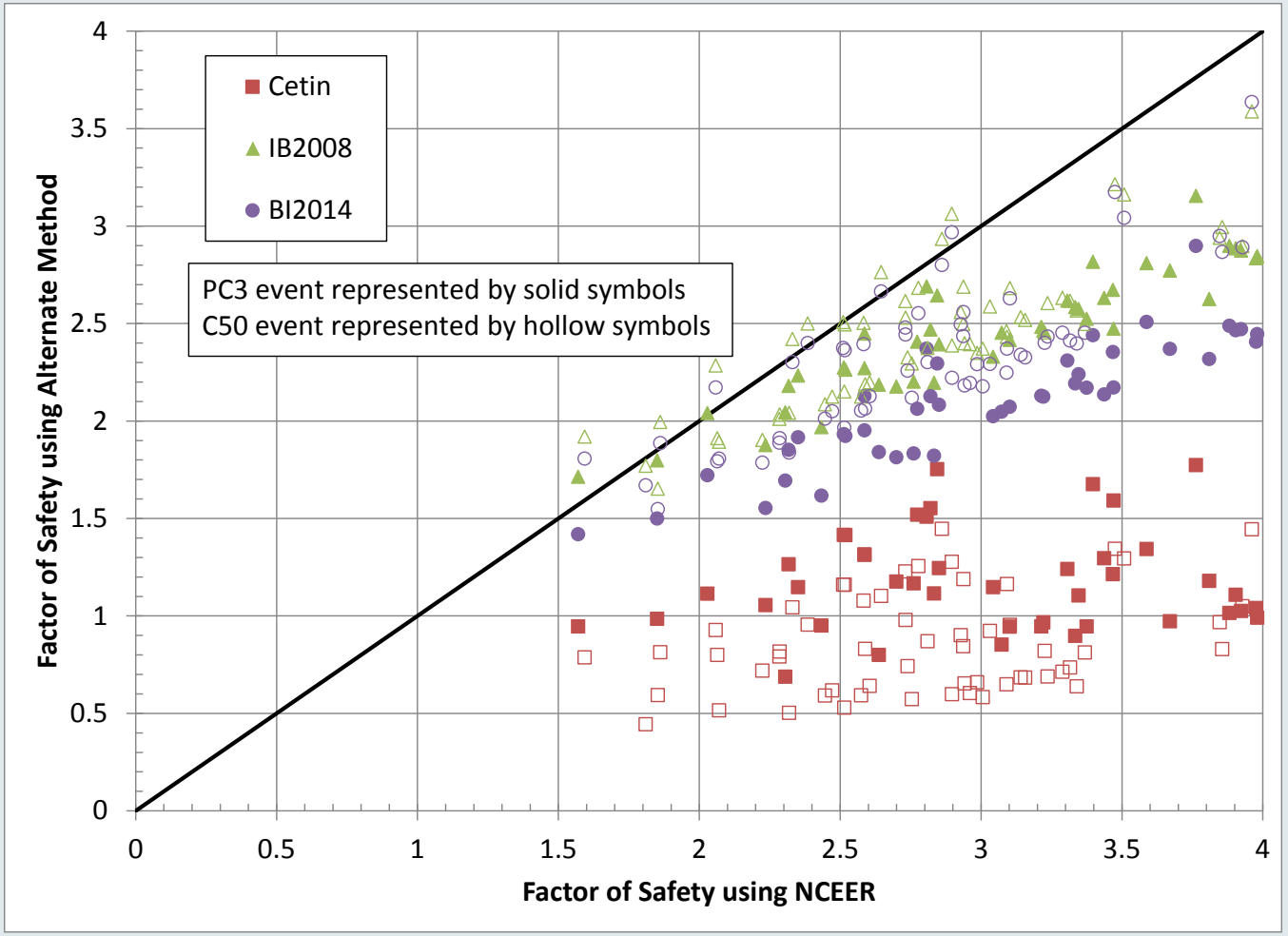
SPT Results at SRS





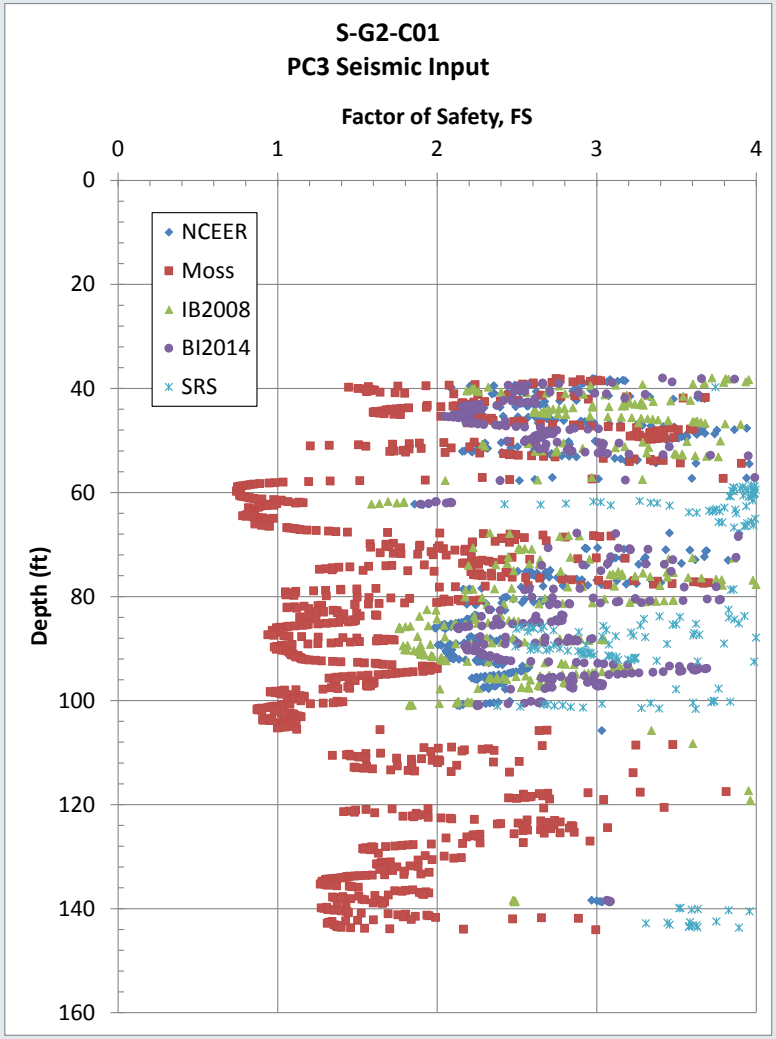
All four relations shown are for Holocene deposits

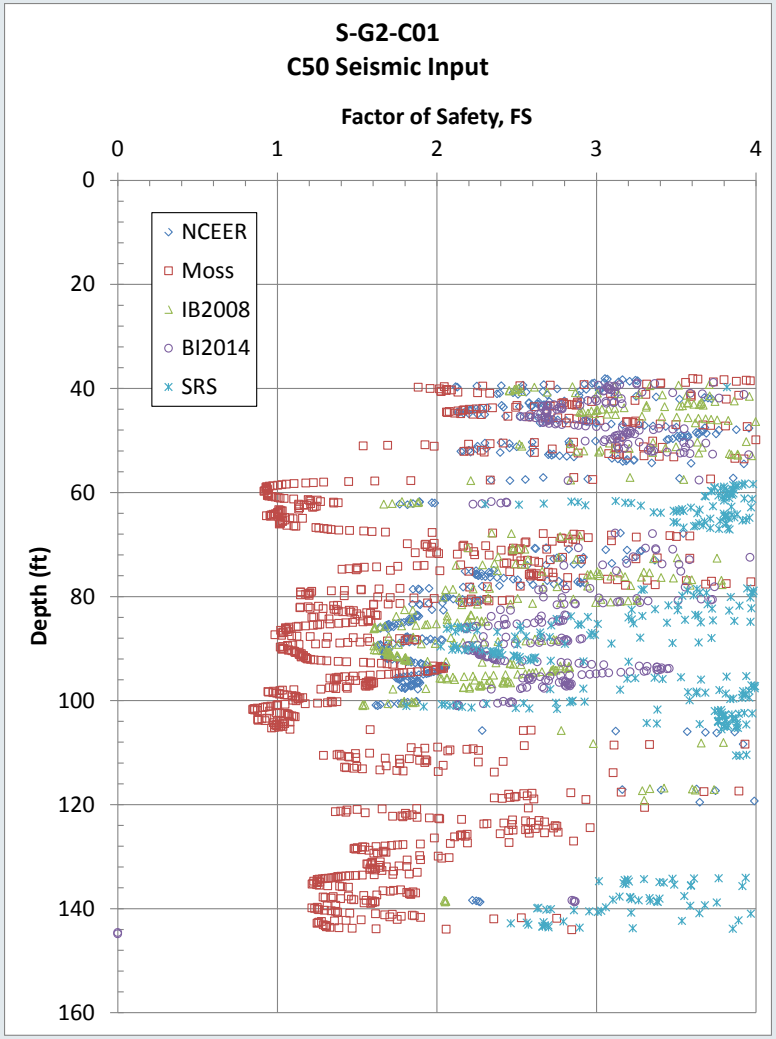
SPT Results at SRS



Combining results from three borings
All relationships are for Holocene deposits

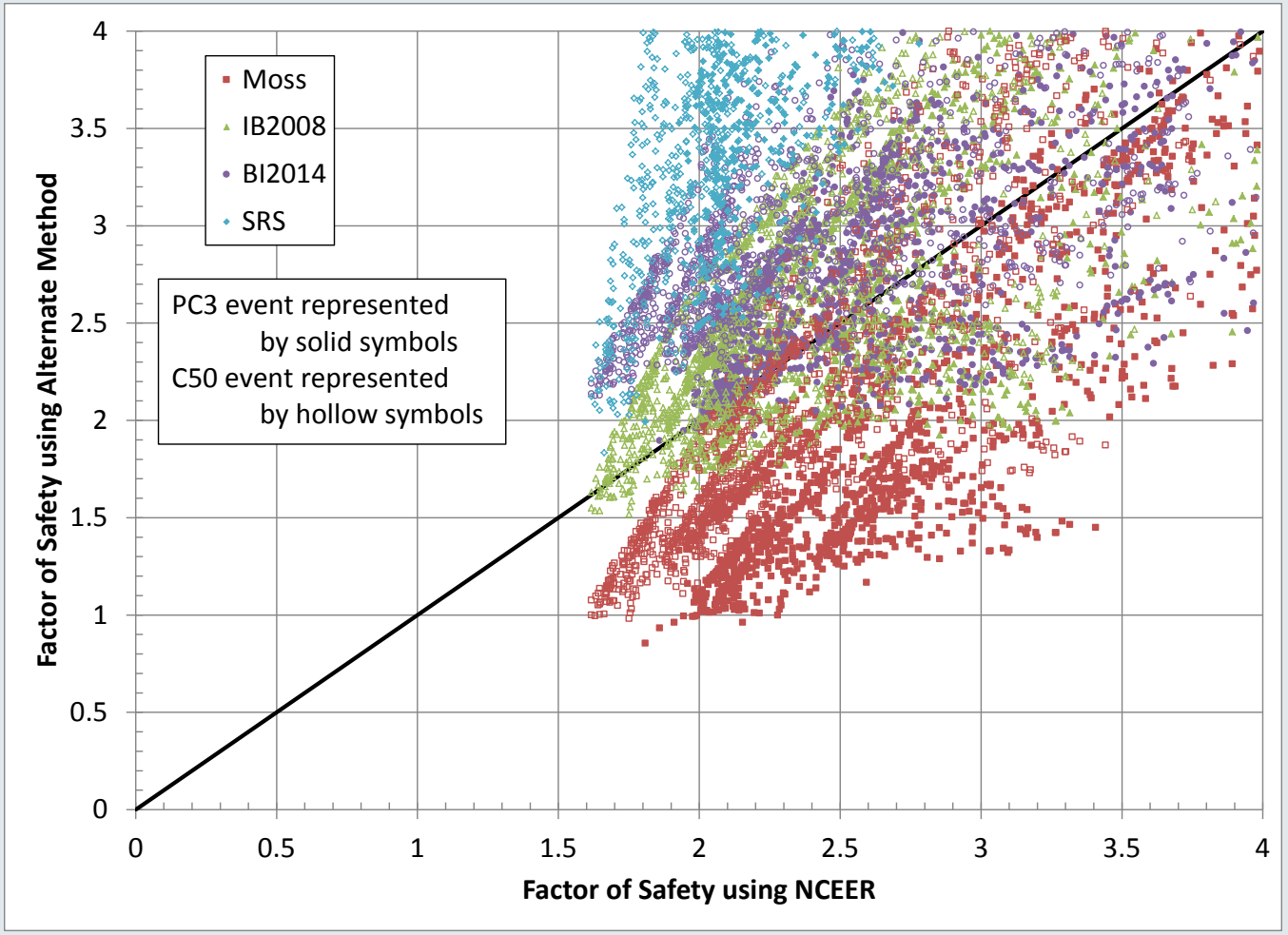
CPT Results at SRS





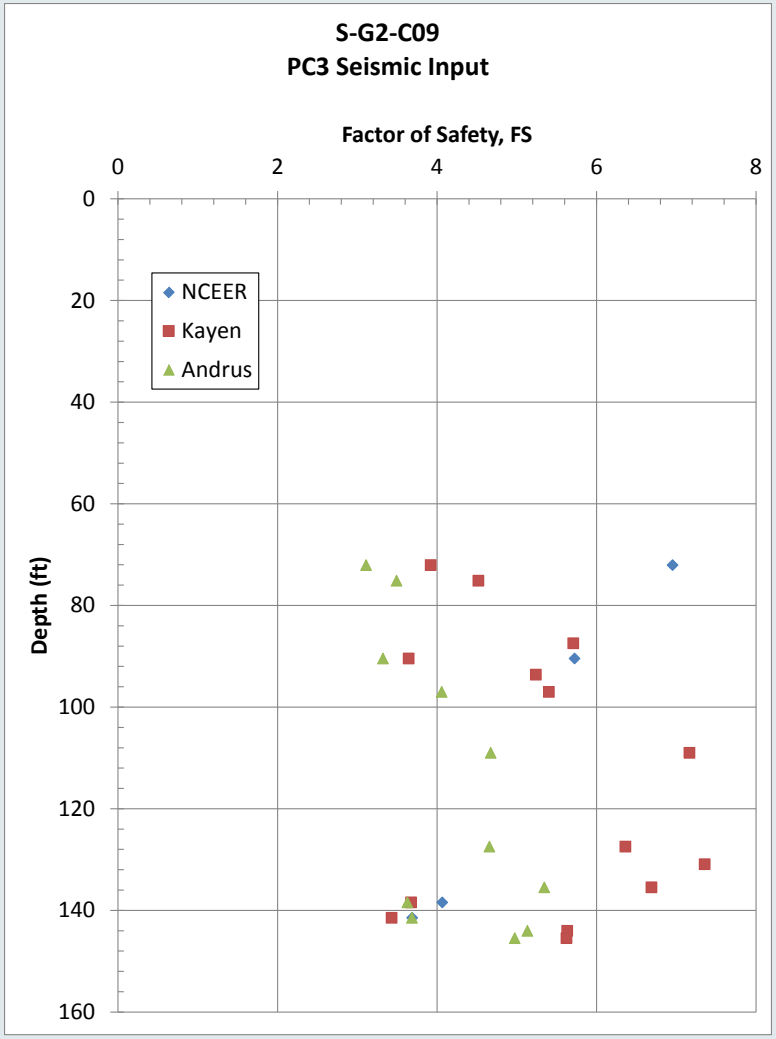
Only SRS accounts for age. All other relationships are for Holocene deposits

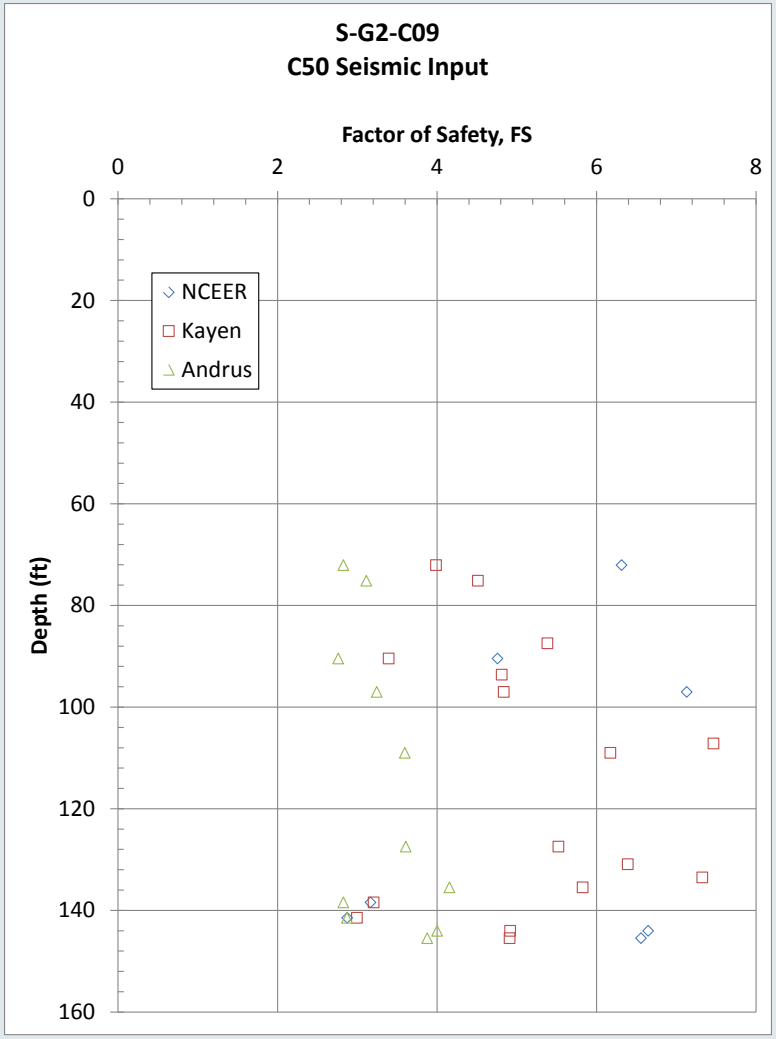
CPT Results at SRS



Combining results from three CPTs
Only SRS accounts for age. All other relationships are for Holocene deposits

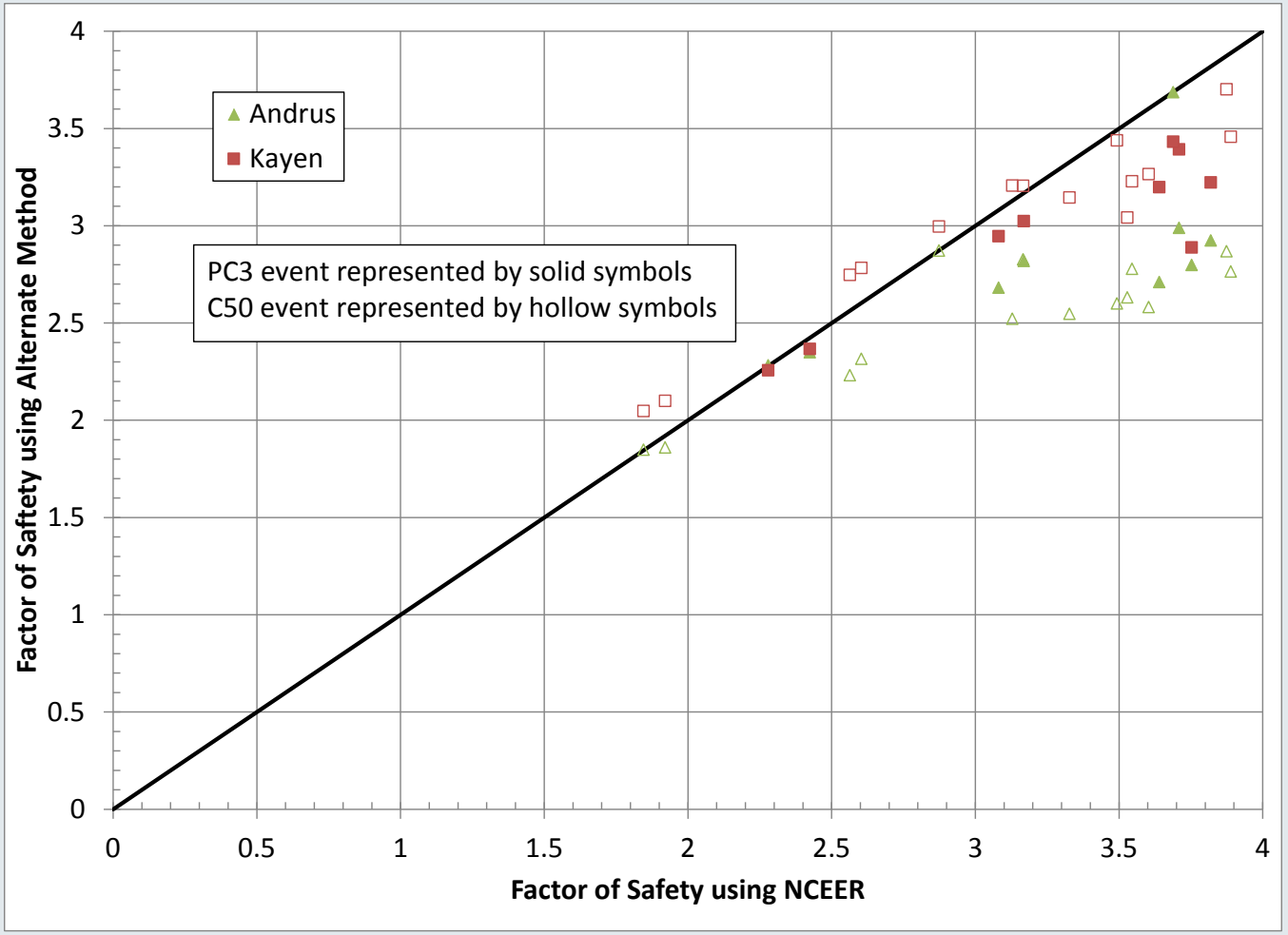
V_s Results at SRS





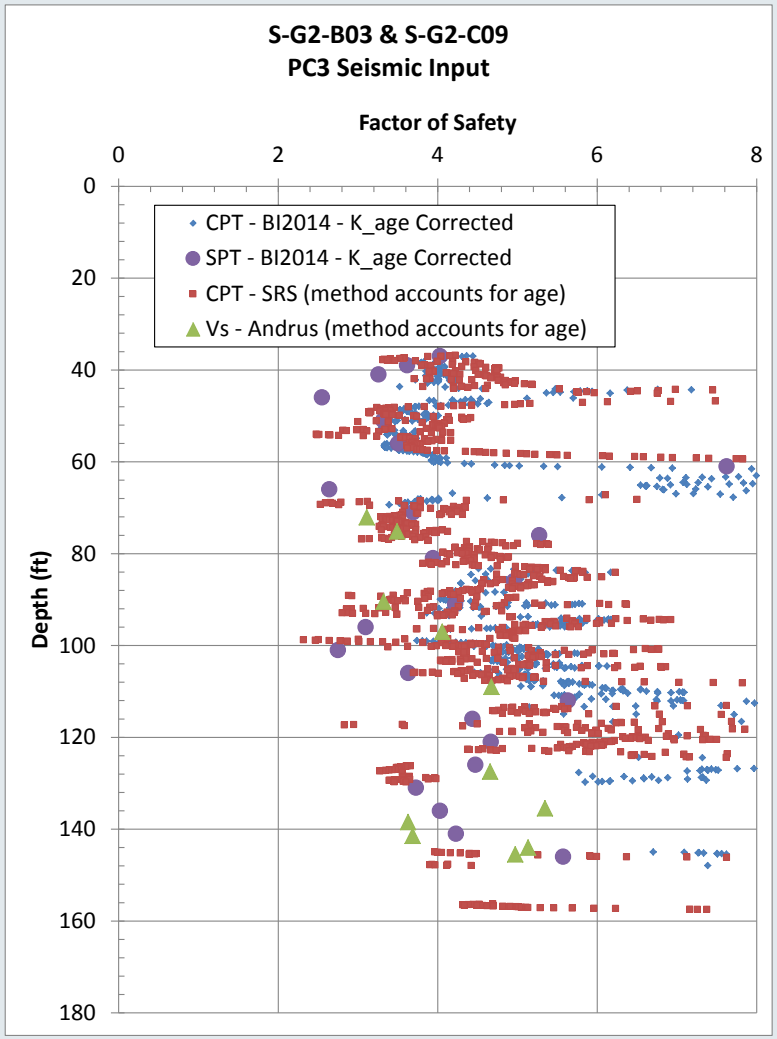
Only Andrus accounts for age. All other relationships are for Holocene deposits

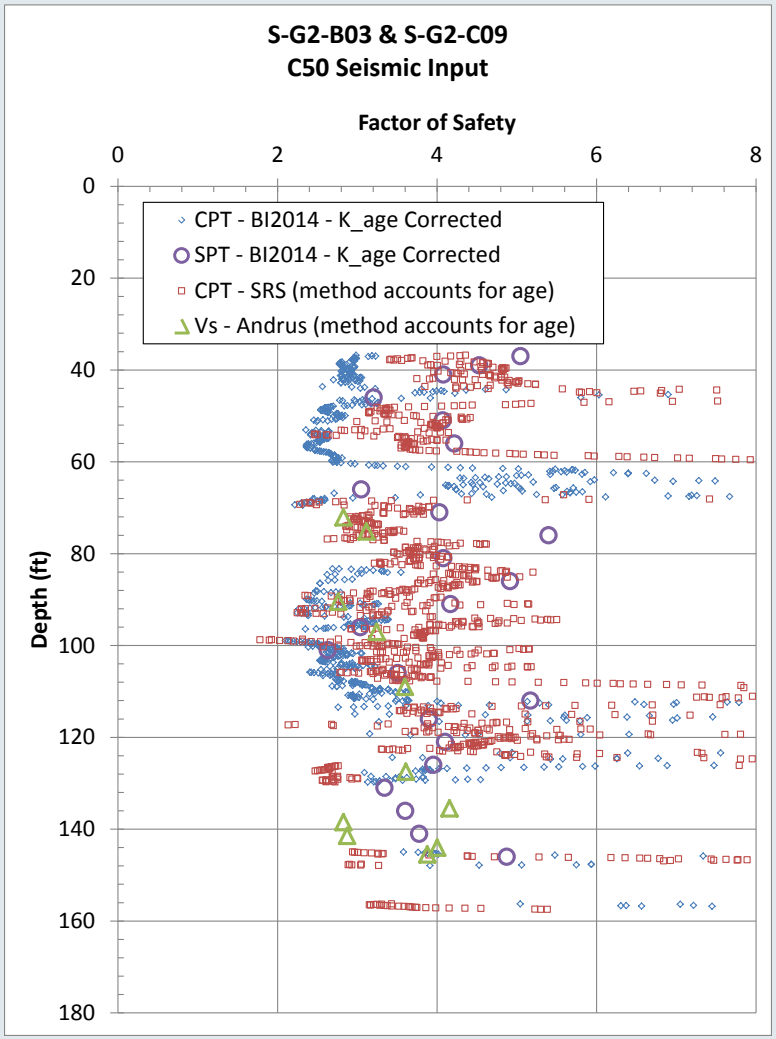
V_s Results at SRS



Combining shear wave velocity results from three SCPTs
Only Andrus accounts for age. All other relationships are for Holocene deposits

Age Corrections





Assumes K_{age} = 1.7 for BI2014

Conclusions

Conclusions

- Advancements in the calculation of magnitude scaling factor (MSF), aging, and fines content correction for the purposes of liquefaction calculations have been presented.
- When accounting for age, the seismic input used result in factors of safety generally greater than 2 for the SRS site.
- The SRS site-specific correlation continues to be appropriate and at the state of practice.

Conclusions

- For the explorations examined and the seismic input motion used, factors of safety are generally distributed as follows:
  - Borings (SPTs)
    - » Using Holocene correlations without correction for age, Cetin has the lowest factor of safety followed by BI2014, IB2008, and NCEER with NCEER having the highest factor of safety.
  - CPTs
    - » Using Holocene correlations without correction for age, Moss has the lowest factor of safety followed by IB2008, BI2014, and NCEER with NCEER having the highest factor of safety. When the SRS site specific relation is used, which accounts for age, the SRS relation results in the highest factor of safety.
    - » When an aging factor is applied to BI2014, the results are similar to those from SRS which accounts for age.
  - V_s
    - » Kayen and NCEER are Holocene correlations which result in similar factors of safety. Andrus, which accounts for age, results in slightly lower factors of safety.

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Questions